

Reducing the magnetic susceptibility of parts in a magnetic gradiometer

Andrew Sunderland^{a,*}, Li Ju^a, Wayne McRae^{a,b},
David G Blair^a

^a*School of Physics, University of Western Australia, Perth, WA, Australia*

^b*Gravitec Instruments, Perth, WA, Australia*

Abstract

In this paper we report a detailed investigation of a number of different materials commonly used in precision instrumentation in the view of using them as critical components in the magnetic gradiometer. The materials requirement inside a magnetic gradiometer is stringent because the presence of magnetic susceptible material will introduce intrinsic errors into the device. Many commercial grade non-magnetic materials still have unacceptably high levels of volume magnetic susceptibility between 10^{-3} and 10^{-4} . It is shown here that machining with steel tools can further increase the susceptibility by up to an order of magnitude. The ability of an acid wash to remove this contamination is also reported. Washing in acid is shown to reduce the variation of volume susceptibility in several commercial grade plastics which already have low values of susceptibility.

Key words: magnetic properties, magnetometer, metals, polymers

PACS: 07.55.Yv

1 Introduction

1.1 Magnetic Gradiometers

A major application for magnetic gradiometers is measuring the gradient of the magnetic field produced by nearby geological targets at distances of 30 m to 100 m[1]. Magnetic material may also be present inside the gradiometer,

* Corresponding author. Tel.: +61 422 282 438.

Email address: asund@physics.uwa.edu.au (Andrew Sunderland).

inside attached equipment and cables, or inside the vehicle used to deploy the gradiometer. All of these pieces of equipment will produce their own magnetic gradients. Whereas magnetic fields from far field dipole sources scale as the inverse third power of distance, magnetic gradients scale as the inverse fourth power and are particularly sensitive to close objects.

Recently, a Direct String Magnetic Gradiometer (DSMG) has been developed, which employs a single "string" as the sensing element[2]. The use of a long and thin sensing element in the DSMG means that a significant number of instrument components are near the sensor string where even relatively small levels of magnetic contamination can lead to false signatures many times larger than the signal from the distant geological target.

The magnetic material inside the sensor generates both induced and remanent magnetisation. The later produces a constant magnetic gradient that can be subtracted from the signal without impeding the operation of the magnetic gradiometer whereas induced magnetisation aligns in the Earth's magnetic field. If the sensor is rotated while being deployed in a moving vehicle, the magnetic gradient produced by induced magnetisation will vary. This varying distortion in the measured magnetic gradient is called heading error. Here we report an investigation of reducing susceptibilities of different materials with a view to reducing the amount of heading error in this particular type of magnetic gradiometers.

1.2 Reasons for measuring the magnetic susceptibility

For small values of magnetic field, the magnetisation rises linearly with applied magnetic field strength. This means that the induced magnetisation per unit volume from a component is equal to the volume susceptibility of the material multiplied by the strength of the applied field (which in this case is the Earth's 30 000 nT to 60 000 nT field). The magnetic field in the space surrounding a magnetised object scales as the inverse third power of distance. Therefore induced magnetisation will produce a heading error that will depend on the distance of the component from the sensing element of the magnetic gradiometer, the volume of the component, any anisotropy in the shape of the component, and the volume magnetic susceptibility of the component.

There is more data in the literature on the remanent magnetic moment of acid washed samples (see below). Nevertheless, in this paper volume susceptibility is required to quantify the amount of heading error a material will produce.

1.3 Prior work

Measurements of the magnetic susceptibility before and after an acid wash have been well known in the literature, see for example Spencer and John[3]. Spencer and John washed their samples in hydrochloric acid to remove possible traces of iron and repeated until a constant value was obtained for the susceptibility. The acid wash was incidental to Spencer's paper and the actual susceptibility values were not reported. Much advice about avoiding magnetic effects in industry is based on oral tradition (for example use phosphor bronze and there will be no problem).

Honda measured the mass magnetic susceptibility of various pure metals, in different forms such as ingot, wire or cast[4]. Honda also recorded the concentration of iron and the chemical form that the iron impurity takes inside the base metal. Honda found only insignificant variation in susceptibility between different metal forms.

Constant and Formwalt measured the remanent magnetic moment of a series of metals[5]. Measurements were taken of both the commercial grade metal and the chemically pure metal. Commercial brass was reported to have the highest magnetic moment, followed by commercial copper and silver. More recently Keyser and Jefferts[6] measured the magnetic susceptibility of a wide variety of laboratory construction materials.

Measuring the volume magnetic susceptibility is not the optimum way to identify small amounts of ferromagnetism because the magnetic susceptibility in the material could be due to diamagnetism, paramagnetism as well as ferromagnetism. On the other hand, measuring a non-zero remanent magnetic moment when the external field is zero is a definite indication of ferromagnetism (although soft iron ferromagnets can have high susceptibility and near zero remanence). Remanent magnetic moment measurements are the principal method of checking a sample for magnetic contamination, see for example Matsubayashi et al[7] or Wang et al[8].

2 Typical magnetic materials

The three ferromagnetic elements (Fe, Ni and Co) have very high susceptibilities, the highest being the initial relative magnetic permeability of 99.9% pure iron $\mu_r = 25000$ [9]. When trying to reduce the magnetic contamination it is not enough to merely avoid the use of pure iron, nickel or cobalt parts because other nonferrous metals of commercial grade are often less than 99% pure and usually contain iron as an impurity.

Brass is often used as a nonmagnetic substitute to replace iron in parts that require high strength or density[10], but the magnetic volume susceptibility of brass varies considerably and care must be taken when choosing a supplier. Generally volume susceptibility will increase with increasing iron content, although the susceptibility will be higher if the iron impurity is concentrated in small clumps[11] or if precipitation of iron occurs during heat treatment[12]. Small amounts of iron (< 0.05%) can alloy with the copper in brass to produce an alloy with a volume magnetic susceptibility proportional to the square of the iron concentration[13].

The complete analysis of the susceptibility of brass is quite complicated as other factors such as heat treatment, cold working and oxygen concentration can have a large effect, see for example Fickett and Sullivan[14]. Parts inside the DSMG are expected to be exposed to large temperature extremes during construction and operation. Relying on a heat treatment to lower the susceptibility of a magnetic gradiometer is not sufficiently robust for all environments. For this reason the susceptibility values of prior work quoted in this paper are all referring to the susceptibility of the material as cast or formed which tend to be higher than textbook values. Fig. 1 shows some previous work on volume susceptibility vs. iron concentration for yellow brass (60-70% Cu, 30-40% Zn). The graph shows a good fit with the square law at low iron concentrations.

If an isotropic very low magnetic susceptibility is required then metals with more than 0.01% iron should not be used. Unreinforced plastics are the best materials to use in extreme nonmagnetic conditions since they have very low levels of impurities[15]. The three unreinforced plastics (Torlon 4203, PET and PTFE) in Table 1 all have less than 0.0001% iron. The composite materials (Torlon 4301 and G10) and the ceramic (macor) have higher impurity levels although not as high as the impurity levels of the metals. The exception is 99.95% pure oxygen free highly conductive copper. Pure metals can have lower impurity levels than commercially available alloys[15].

3 Hacksaw contamination

In addition to the volume susceptibility of the bulk of the material, there can also exist residual contamination from the machining of parts that produces a significant surface contribution to induced magnetisation. To investigate this surface contribution, 14 samples of 7 different materials were cut to dimensions 12 mm x 16 mm x 16 mm with a high carbon steel hacksaw. In addition two M3 holes were tapped with a tap made from tool steel. Depending on the abrasiveness of the sample in question, some of the steel on the tools will be deposited into the surface of the samples during machining. Table 2 shows that the initial relative magnetic permeability of a hacksaw blade can be as high

as $\mu_r = 11$ compared to magnetic susceptibilities of $\chi_{diamagnet} \approx -10^{-5}$ for a typical diamagnet. This means that even small amounts of steel contamination can produce unacceptably high heading error.

To remove any surface magnetism, the samples were immersed in 3% concentrated hydrochloric acid. Low field volume susceptibility readings were taken before and after immersion using a Bartington MS2b susceptibility meter for the metal samples and a ZH Instruments SM-30 susceptibility meter for the plastic and ceramic samples. The DSMG operates at room temperature, hence all susceptibility measurements in this paper were taken at room temperature. All susceptibility values are volume susceptibility in SI (MKS) units. Concentrations in samples are stated by mass.

Fig. 2 shows the change in volume susceptibility before and after acid treatment for each of the plastic and ceramic samples. The graph shows a slight decrease in the volume susceptibility of the plastic and ceramic samples after a 24 hour acid wash. There is very little contamination to remove from any of the plastic and ceramic samples, with the exception of G10 (G10 is significantly more abrasive than the other plastics and removes more iron from tools during machining). The advantage of immersing the plastic samples in acid was that the volume magnetic susceptibility had less variation after the acid wash and that the magnetisation was more isotropic. The volume susceptibility of samples as machined varied $\pm 2 \times 10^{-6}$ when rotated to different orientations whereas the volume susceptibility of acid washed samples varied only $\pm 10^{-6}$. Hydrochloric acid removes surface iron from all samples, but when it is applied to metallic samples hydrochloric acid may also corrode the surface of the metal. To evaluate the rate that hydrochloric acid corroded the metal samples, each of the samples was immersed in hydrochloric acid for durations of 10 minutes, 70 minutes, and 24 hours. Table 3 shows some loss of mass from acid washing. In particular the corrosion in the aluminium sample after 24 hours produced a significant 7% reduction in the mass.

Fig. 3 shows that immersing the metallic samples in acid for only 10 minutes removes nearly all the surface contamination and reduces the volume susceptibility by an order of magnitude. An acid wash of 70 minutes produces no further reduction in the volume susceptibility. From this result it can be inferred that the remaining induced magnetism is caused by small but significant concentrations of iron in the body of the sample. A 10 minute acid wash is therefore optimal for reducing heading error from brass and aluminium parts because immersing parts in acid for longer durations of time may corrode parts to the extent that they cease to be within design tolerances.

The volume susceptibility of the metallic samples before acid washing are approximately 3 orders of magnitude higher than the plastic samples before acid washing. This indicates that the more abrasive metal samples are more

easily contaminated with the high carbon steel in the hacksaw.

The value of the volume magnetic susceptibility of the acid washed aluminium 6061 sample measured by the authors does not agree with previous work by Keyser and Jefferts[6]. This could be due to different amounts of magnetic contamination between samples or an erroneous response of the Bartington MS2 to electrical conductivity in the sample as shown in Benech and Marmet[16]. However, for the purpose of this paper, in order to avoid any possible ambiguity in getting samples with different contamination levels, the use of such materials should be avoided. The red brass susceptibility value recorded by the authors does agree with previous work as shown in Fig. 1.

4 Lathe contamination

10 samples of 5 different materials, were cut on a lathe with a tool bit made from high speed steel. The samples were machined on the lathe to make cylinders of diameter 5 mm and length 5 mm in order to fit in a Vibrating Sample Magnetometer (VSM). A single M3 hole was tapped along the axis with a tool steel tap. The 8 metal samples were immersed in acid for 10 minutes and the 2 Torlon samples were immersed for 24 hours. Volume susceptibility measurements were taken before and after immersion following the same procedure used for the larger samples.

Fig. 4 shows the change in volume susceptibility before and after acid treatment for each of the samples. The smaller cylindrical samples should have a higher relative surface contamination due to the large surface to volume ratio. However, the volume susceptibility of the unwashed aluminium cylindrical sample is a factor of three less than its hacksawed counterpart. This is most likely because the relative permeability of the lathe tool bit is only 1.4 compared to a relative permeability of 11 for the hacksaw blade. Another factor is that the lower hardness of the carbon steel hacksaw blade listed in Table 2 will allow the blade to deposit more steel onto the surface of the sample

The unwashed red brass and copper cylindrical samples have almost the same value for volume susceptibility of 2.2×10^{-4} . This value is two orders of magnitude lower than the hacksaw contaminated brass sample. This indicates that copper and copper alloys are difficult to contaminate with high speed steel.

The yellow brass sample has a very high bulk susceptibility and the percentage change after an acid wash was unmeasurably small. The volume susceptibility of the washed cylindrical samples was lowest for the materials with the least amount of iron. The OFHC copper sample with 0.0002% Fe has a volume susceptibility of 3×10^{-5} and Torlon 4301 with 0.0002% Fe has a volume

susceptibility of 2×10^{-5} .

There is a discrepancy between the volume magnetic susceptibility of OFHC copper measured using the VSM and the textbook value of -1×10^{-5} [17]. This could be due to an imperfect acid wash or the limited accuracy of the VSM of $\pm 10^{-5}$ for samples of this size. Despite this inaccuracy, the results of the VSM are show that an acid wash can reduce the volume suspectibility below 10^{-4} which is sufficient for reducing heading error.

5 Varying applied field measurements

In addition to the low field volume susceptibility measurements, a complete scan of the magnetisation at different applied fields up to 1 T was preformed on the two 5 mm diameter Torlon cylinders. Two additional measurements were made at -7 T and 7 T to check the diamagnetic contribution. The measurements were taken using a Quantum Design MPSM-7 Superconducting Quantum Interference Device (SQUID) before and after immersion in acid.

From the gradient at the origin (low field case) in Fig. 5, the volume susceptibility of the unwashed and washed samples are both positive with values of 3.6×10^{-5} and 2.0×10^{-5} respectively. When the applied magnetic field exceeds $\mu_0 H > 0.1$ T the magnetisation has saturated and the volume susceptibility becomes negative. The high applied field susceptibilities for the unwashed and washed samples are -1.4×10^{-5} and -1.7×10^{-5} respectively. These values indicate that Torlon is diamagnetic so that a pure sample with no iron contamination should have a volume susceptibility near -1.7×10^{-5} in both low and high applied fields. The presence of a positive susceptibility that saturates in a modest applied magnetic field indicates the presence of a small amount of ferromagnetism.

Immersing the sample in acid reduced the low field volume susceptibility from 3.6×10^{-5} down to 2.0×10^{-5} . The acid wash removed all surface contamination and reduced the ferromagnetic contribution of the entire sample by 30%. The remaining ferromagnetism in the washed sample is produced by the bulk of the sample.

After subtracting the diamagnetic contribution to magnetisation, what is left is the magnetisation from ferromagnetic sources alone. Fig. 5 shows that this ferromagnetic contribution in the washed Torlon saturates at a magnetisation of $\mu_0 M = 4.1 \mu\text{T}$. By comparison pure iron saturates at a magnetisation of $\mu_0 M = 2.15$ T, nickel saturates at $\mu_0 M = 0.69T$ and cobalt saturates at $\mu_0 M = 1.79$ T[18]. Assuming the ferromagnetic contribution is all due to Fe, the ferromagnetic iron in this Torlon 4301 sample is about 10 parts per million

by mass. The result of 0.086% Fe from elemental analysis suggests that almost all of the iron is in a paramagnetic state, a consequence of the iron being evenly dissolved into the Torlon.

There is a discrepancy between the low field susceptibilities of the washed 5 mm diameter Torlon cylinder and the susceptibility of the washed larger 12 mm x 16 mm x 16 mm prism. Possible causes could be a large anisotropy in the induced magnetism or that the acid is not removing all of the surface ferromagnetism which is more significant in the smaller samples. Despite the discrepancy, the change in volume susceptibility after an acid washed was negligible for both the cylinder and the prism.

6 Conclusion

With regard to minimizing heading error in a magnetic gradiometer, plastics and ceramics parts that were measured had the lowest values for volume susceptibility $\chi_{plastic} \sim 10^{-5}$. In addition the effect of machining plastic with steel tools produced negligible contamination. Metallic parts may however be required for their high conductivity or strength. Metals with less than 0.01% iron, which have been acid washed can also have susceptibilities below 10^{-4} , comparable with plastics. Machining metals with high speed steel is preferred to high carbon steel as it produces less contamination. Metallic samples should be immersed in 3% concentrated hydrochloric acid for an optimum time of 10 minutes.

Washing plastic or ceramic parts in acid will reduce the volume susceptibility by only a insignificant amount. Out of the acid washed samples, the volume magnetic susceptibility closest to zero was -6×10^{-6} from PTFE. Susceptibilities significantly lower than that of PTFE in solid parts can only be achieved by using specially designed alloys that offset paramagnetism with diamagnetism. Nevertheless using expensive alloys is not necessary since even assuming maximum asymmetry, volume susceptibilities of order 10^{-5} will produce heading error in the DSMG of order 10 nT/m peak which is less than the typical heading error of 20 nT/m peak from the vehicle used to deploy the gradiometer. The anisotropy in the volume susceptibility of acid washed plastics is only $\pm 10^{-6}$. A reduction in the anisotropy of magnetic impurities coupled with symmetry in the sensor could reduce heading error. We intend to investigate this in future work.

Acknowledgements

The authors would like to thank Dr. Alexey Veryaskin and Mr. Howard Golden of Gravitec Instruments for many useful discussions and suggestions, A/Prof. Tim St Pierre of the BioMagnetics and Iron BioMineralisation group at UWA for the use of the wet acid laboratory, Dr. Robert Woodward of the Nanomagnetics and Spin Dynamics Group at UWA for the SQUID and VSM measurements, Prof. Li of the Tectonic Special Research Center at UWA for the use of a MS2b susceptibility meter, Mr. Barry Price of the Chemistry Centre of WA for elemental analysis and Mr. Mads Toft of Alpha Geoscience for the use of a SM-30 susceptibility meter. Work on the DSMG project is funded in part by a linkage grant from the Australian Research Council.

References

- [1] M.F. Mushayandebvu, J. Davies, *The Leading Edge* 25 (2006) 69.
- [2] H. Golden, W. McRae, A. Sunderland, A.V. Veryaskin, D.G. Blair, L. Ju, in: Australian Institute of Physics 17th National Congress, Sydney, 2006.
- [3] J.F. Spencer, M.E. John, *Proceedings of the Royal Society A* 116 (1927) 61.
- [4] K. Honda, *Annalen der Physik* 337 (1910) 1027.
- [5] F.W. Constant, J.M. Formwalt, *Physical Review* 56 (1939) 373.
- [6] P.T. Keyser, S.R. Jefferts, *Review of Scientific Instruments* 60 (1989) 2711.
- [7] K. Matsubayashi, M. Maki, T. Tsuzuki, T. Nishioka, N.K. Sato, *Nature* 420 (2002) 143.
- [8] W. Wang, Y. Hong, M. Yu, B. Rout, G.A. Glass, J. Tang, *Journal of Applied Physics* 99 (2006) 08M117.
- [9] R.A. McCurrie, *Ferromagnetic materials*, Academic Press, London, 1994, p. 42.
- [10] P. Webster, *The Brasses - Properties & Applications*, Copper Development Association, Hemel Hempstead, 2005, p. 5.
- [11] F.B. Huck, W.R. Savage, J.W. Schweiter, *Physical Review B* 8 (1973) 5213.
- [12] A. Butts, P.L. Reiber, *Journal of Geophysical Research* 54 (1949) 303.
- [13] H.E. Ekstrom, H.P. Myers, *Zeitschrift für Physik B Condensed Matter* 14 (1972) 265.
- [14] F.R. Ficket, D.B. Sullivan, *Journal of Physics F Metal Physics* 4 (1974) 900.

- [15] 2002 Goodfellow Catalog of Metals & Materials, Goodfellow Cambridge, Huntingdon, 2002.
- [16] C. Benech C, E. Marmet, Archaeological Prospection 6 (1999) 31.
- [17] J.R. Davis (Ed.), ASM Specialty Handbook: Copper and Copper Alloys, ASM International, Materials Park, 2001, p 487.
- [18] S. Zhou, Electrodynamics of Solids and Microwave Superconductivity, John Wiley & Sons, New York, 1999, p 90.
- [19] J.R. Barker, Journal of Scientific Instruments 25 (1948) 363.
- [20] J. Gattacceca, P. Eisenlohr, P. Rochette, Geophysical Journal International 158 (2004) 42.
- [21] P. Havrey (Ed.), Engineering Properties of Steel, ASM International, Materials Park, 1982.

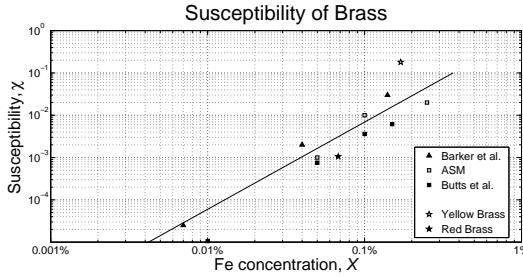


Fig. 1. The susceptibility of yellow brass rises rapidly with increasing iron concentration. The data is compiled from a paper by Barker et al[19], a book by ASM International[17], a paper by Butts et al[12] and measurements performed by the authors on yellow and red brass samples. The line is a best fit at low Fe concentrations using a square law $\chi \propto X^2$.

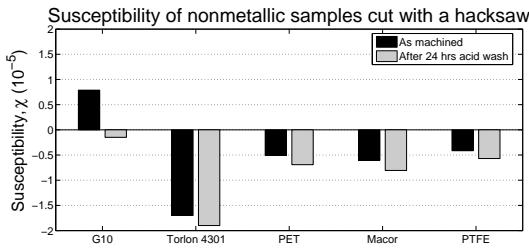


Fig. 2. Low field ($< 50 \mu\text{T}$) susceptibility of plastic and ceramic samples before and after a acid wash. Data taken using a ZH Instruments SM-30 susceptibility meter which has uncertainty of $\pm 10^{-6}$ for samples of this size. An adjustment for sample volume in the SM-30 was done using a formula derived by Gattacceca et al[20] which has an uncertainty of $\pm 20\%$.

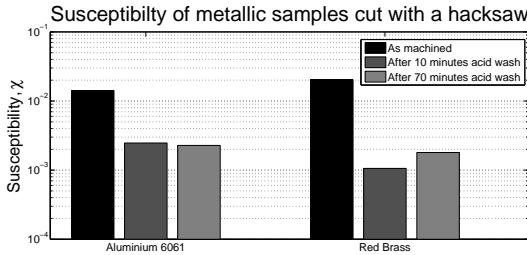


Fig. 3. Low field ($< 250 \mu\text{T}$) susceptibility of metallic samples before and after acid washes. Data taken using a Bartington MS2b susceptibility meter which has uncertainty of $\pm 10^{-5}$ for samples of this size.

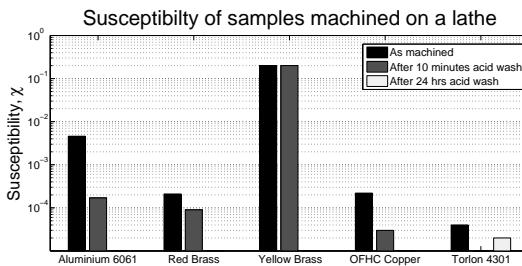


Fig. 4. Low field ($< 0.02 \text{ T}$) susceptibility of cylindrical samples before and after acid washes. Data taken using a Aerosonic 3001 Vibrating Sample Magnetometer which has uncertainty of $\pm 10^{-5}$ for samples of this size.

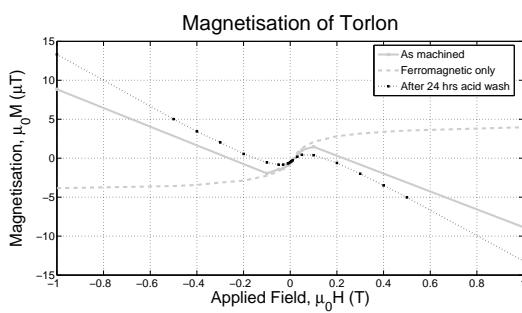


Fig. 5. Magnetisation of Torlon sample 2 in applied fields from -1 T to 1 T before and after acid washes. The dashed line is an inferred curve of the ferromagnetic contribution to the magnetisation of the acid washed samples. Data taken using a Quantum Design MPSM-7 SQUID. The SQUID has a precision of $\pm 0.2 \text{ nT}$ magnetisation for samples of this size although the accuracy is $\pm 5\%$ due to imperfect alignment of the samples.

Sample material	Nominal concentrations (ppm)			Elemental analysis (ppm)		
	Fe	Ni	Co	Fe	Ni	Co
G10				26.	<0.2	<0.1
Torlon 4203	0.1	<0.1	<0.1			
Torlon 4301				860.	4.5	1.1
PET	<0.1	<0.1	<0.1	<5.	<0.2	0.4
Macor				700.	7.	590.
PTFE	<0.1	<0.1	<0.1	<5.	<0.2	<0.1
Red Brass	<3000	<10000	<10000	680.	180.	0.7
Yellow Brass	<5000	<5000	<5000	1700.	1500.	7.5
Aluminium 6061	<7000	<5000	<5000	1700.	45.	<0.1
OFHC Copper	2.	<1.	<1.	<5.	1.3	<0.1

Table 1

Nominal concentrations were taken from material datasheets. Elemental analysis was performed by the Chemistry Centre of Western Australia using a Inductively Coupled Plasma - Atomic Emission Spectrometer (ICP-AES).

Tool	Material	Relative Permeability	Hardness Rockwell C
Lathe tool bit	High speed steel	1.4	64 to 65
M3 Tap	Tool steel	3.7	61 to 62
Hacksaw blade	High carbon steel	11.	59

Table 2

The permeability measurements were made with a Bartington MS2b susceptibility meter. The permeability of the tools varied $\pm 30\%$ when rotated. Hardness values are from a book by ASM International[21].

Metal	Mass as machined(g)	Mass after 10 minutes(g)	Mass after 70 minutes(g)	Mass after 24 hours(g)
Brass	24.68	24.68	24.68	24.67
Al	8.05	8.05	8.04	7.46

Table 3

The mass reduction of metal samples in acid increases with longer immersion times, uncertainty is $\pm 0.01\text{g}$.